





Submitted to the Astrophysical Journal

## Radio Monitoring of the January 11, 1997 Gamma-Ray Burst

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### ABSTRACT

We report on a comprehensive radio monitoring program of the bright gamma-ray burster GRB 970111. These VLA observations were made at a frequency of 1.4 GHz ( $\lambda = 20$  cm) and span a range of post-burst timescales between 28 hours and one month. Despite extensive sampling at sub-milliJansky sensitivities, no radio source was detected above 0.5 mJy in the current best error box ( $\sim 14$  arcmin<sup>2</sup>) for GRB 970111. A highly unusual radio source, VLA J1528.7+1945, was seen to drop in flux density by a factor of two in our monitoring period but it lies outside the error box and thus it is unlikely to be related to GRB 970111. Cosmological fireball models of gamma-ray bursts make predictions of late-time emission occurring at longer wavelengths. The absence of a flaring or fading radio counterpart to GRB 970111 provides strong constraints on these models.

*Subject headings:* gamma rays: bursts - radio continuum: general

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## 1. Introduction

The identity of gamma-ray bursters (GRBs) has remained a mystery since their discovery more than three decades ago (Klebesadel, Strong & Olson 1973). These brief but intense flashes of gamma-rays are isotropically distributed on the sky, but the distribution of burst brightnesses appears to be inhomogeneous, in particular showing a deficit of fainter events (Meegan et al. 1992). The existing data cannot unambiguously distinguish whether GRBs originate in a halo around our Galaxy (Lamb 1995) or at cosmological distances (Paczynski 1995).

The detection and identification of a GRB counterpart at other wavelengths has the potential to make significant progress in our understanding of the origin of GRBs. Cosmological models predict that a radio outburst will follow the gamma-ray outburst (Paczynski & Rhoads 1993, Mészáros & Rees 1997), albeit delayed and with decay timescales of order a few days to weeks. There have been previous searches for radio counterparts of GRBs (e.g. Schaefer et al. 1989, Palmer et al. 1995, Dessenne et al. 1996), but none so far have presented a serious challenge to predictions of the cosmological models. The principal difficulty has been in obtaining sensitive radio observations over the full range of the relevant timescales. The observations of GRB 940301 were the first to continuously sample a range of post-burst timescales between 3 and 15 days, as well as 26, 47 and 99 days (Frail et al. 1994), but only to a limit of 3.5 mJy at  $\lambda = 20$  cm.

With the launch of Satellite per Astronomia a raggi X or BeppoSAX on April 30 1996 it became possible to use the Very Large Array (VLA) to do a full monitoring of events at high sensitivity over a range of post-burst timescales. The gamma-ray burst experiment on BeppoSAX consists of two parts: the Gamma-Ray Burst Monitor (Frontera 1997) (60-600 keV) and the Wide Field Cameras (2-30 keV) (Jager et al. 1996), and is capable of detecting approximately  $5 \pm 2$  bursts per year with  $f_\gamma > 10^{-6}$  erg cm $^{-2}$  (40-600 keV) and localizing them with a position error of several arcminutes (Piro 1997). Here we present the results of an extensive VLA monitoring campaign of GRB 970111, in which observations were made beginning 28 hours after the burst and continued every several days for up to a month. Prior to these observations the earliest response to a well-localized GRB at the VLA was 9 days (GRB 930706) by Palmer et al. (1995). Furthermore, the sensitivity of our VLA campaign is an order of magnitude improvement over the earlier monitoring effort of GRB 940301 by Frail et al. (1994) on these same timescales.

## 2. Observations

GRB 970111 was detected (Costa et al. 1997a) by the Italian satellite BeppoSAX on January 11.41, 1997 UT. It was seen by both the Gamma-Ray Burst Monitor, and was in the  $40^\circ \times 40^\circ$  field of view Wide Field Camera. The gamma-ray burst had a peak flux of  $4 - 5 \times 10^{-6}$  erg cm $^{-2}$  s $^{-1}$  and lasted for a period of about 50 s. Detection of the burst in the WFC enabled an initial localization of the burst to a circle of radius 10 arcmin (Costa et al. 1997a). Further details about the high energy characteristics of this burst will be published at a later time (Costa et al. 1997b).

The burst localization was further reduced by combining the intersection of the WFC error circle with a timing arc, obtained (Hurley et al. 1997a,b) from burst arrival times between the Ulysses and Compton Gamma Ray Observatory spacecraft. We refer to this error quadrilateral as the BeppoSAX-IPN (Interplanetary Network) error box. Following this, a re-calibration of the WFC by in 't Zand et al. (1997) resulted in a much-reduced error circle for GRB 970111. This new BeppoSAX error circle remains consistent with the Hurley et al. (1997b) IPN but it is 4.2 arcmin from the center of the old BeppoSAX error circle and has a radius of only 3 arcmin. In Figure 1 we present a radio image of this entire region with the different error boxes marked to aid in the subsequent discussion.

The radio observations were conducted at the Very Large Array (VLA), with the first image of the GRB 970111 field made on January 12.58, 1997 UT, only 28 h after the detection of the gamma-ray burst. This was followed by a regular monitoring program of the full 10 arcmin radius WFC error circle at a radio frequency of 1.43 GHz. Table 1 lists the details of the observation. Dates are given for the start of each radio observations (Epoch), as are the time elapsed since the gamma-ray burst ( $\Delta t$ ), the synthesized beam, the rms noise in each image ( $\sigma_{rms}$ ) and the peak flux density ( $S_{1.4}$ ) measured for VLA J1528.7+1945 (see §3 for details). The data were reduced in the usual manner using the AIPS software package.

### 3. Results

Fig. 1 is a radio continuum image at 1.4 GHz towards GRB 970111 taken almost two years earlier, in March 1995, as part of the NRAO VLA Sky Survey (NVSS) (Condon et al. 1997). This is the full field of view covered by our 1997 monitor program of GRB 970111. We have superimposed the different IPN and WFC error regions discussed above. Although the synthesized beamsizes are very different, we find all of the NVSS sources in our monitor data. The majority of these sources are partially or fully resolved at our higher angular resolution. The NVSS survey is complete above 2.5 mJy (the second contour), and so with our better sensitivity we also detect fainter sources ( $S > 0.5$  mJy) with no NVSS counterpart.

The best current error box for GRB 970111 is a trapezoidal region defined by the intersection of the refined IPN annulus (Hurley et al. 1997b) and the new WFC error circle (in 't Zand et al. 1997). Interior to this region we detect no radio sources. While our rms noise limits vary from one day to the next, we can confidently rule out either a constant or time-variable radio source in the error box above 0.5 mJy at  $\lambda=20$  cm over the time period covered in Table 1. This corresponds to limits between  $3\sigma$  and  $8\sigma$ , depending on the integration time used on a given day. Galama et al. (1997) report the detection of a single radio source in the trapezoidal region with a flux density of 0.6 mJy at a frequency of 840 MHz. We have searched our images at this position over the same interval that Galama et al. (1997) claim a detection and we see no such source. In order for this source to have been detected by the Westerbork Synthesis Radio Telescope (WSRT) at 840 MHz but remain undetected at the VLA at 1.4 GHz its spectra index would have to be  $-2.0$ , a

value that is rarely seen except for pulsars. Alternatively, given the large synthesized beam size of WSRT, the source may be erroneous, caused by confusion from a background of unresolved radio sources.

Four radio sources were seen within the larger BeppoSAX-IPN error box but outside the trapezoidal region. The brightest source, VLA J1528.7+1949 was detected in the NVSS. The remaining three sources have average flux densities between 0.4 and 1.4 mJy and are uncatalogued radio sources. From radio source counts (White et al. 1997) we expect 0.025 radio sources per arcmin<sup>2</sup> with flux density above 1 mJy, or  $2 \pm 1$  sources in the BeppoSAX-IPN error box. Thus the detection of four sources is consistent with all these sources being unrelated background radio sources. Two of these, VLA J1528.2+1933 and VLA J1528.6+1940, lie 3.7 arcmin and 4.7 arcmin from the center of the trapezoidal error box.

An X-ray source SAX J1528.8+1944 (Butler et al. 1997) has been noted to coincide, within its localization error of 1-arcmin (radius), with one of the radio sources, VLA J1528.7+1945 (Frail et al. 1997). This source was first detected by the X-ray satellite ROSAT in August 1991 (Voges, Boller & Greiner 1997) and was recently re-detected with the main focal plane cameras aboard BeppoSAX. With the exception of the source VLA J1528.7+1945 the remaining three radio sources in the BeppoSAX-IPN error box are steady sources, as are most background extragalactic radio sources on timescales of days to weeks. A  $\chi^2$  test for radio variability (Machalski & Magdziarz 1993) was carried out on all eight point sources in the original 10 arcmin BeppoSAX error circle. J1528.7+1945 is the only variable source in the field, with a confidence level which exceeds 99.95%. The light curve for VLA J1528.7+1945 is shown in Fig. 2 with several comparison sources. In March 1995 it was undetected above the NVSS limit of 2.5 mJy. Within three to four days after the burst it appears to peak at 2 mJy and decayed to half of this value some 15 days later, where it has remained level since. We will discuss this source in more detail in §4.

## 4. Discussion

### 4.1. Constraints on Cosmological Models

We have imaged a 625 arcmin<sup>2</sup> region around the position of GRB 970111 with the VLA on timescales of days to  $\sim$ months after the initial burst. We have found no radio sources within the  $\sim$ 14 arcmin<sup>2</sup> trapezoidal error box, defined by the intersection of the refined WFC error circle and the IPN. A conservative limit on any flaring or fading radio counterpart to GRB 970111 at  $\lambda = 20$  cm on these timescales is 0.5 mJy. The present VLA observations provide strong constraints on the predictions of late-time emission from cosmological models of GRBs.

The fast risetimes and the energetics of GRBs make it inevitable that GRBs involve a burst of relativistic particles and magnetic fields. The sudden deposition of this energy creates a “fireball” whose physics has been studied by various authors (Mészáros 1995). A generic prediction of these

studies is that the gamma-ray burst is followed by bursts at smaller photon energies but with burst timescales much longer than that at gamma-ray energies and increasingly delayed with respect to the gamma-ray outburst. In models in which the GRBs are of Galactic origin the fireball energy is relatively small and the expectation is that the radio outburst will be essentially prompt. However, in cosmological models, the radio outburst is predicted to be delayed by days to weeks with similar values for the outburst timescales.

The Paczyński & Rhoads (1993) model is a variant on the popular van der Laan (1966) model describing the flux evolution of expanding radio sources taken to its relativistic limit. Some fraction of the bulk kinetic energy of the fireball from the GRB goes into magnetic fields and a relativistic electron population with a power-law distribution of energies. Baryons account for the majority of energy in the fireball, the energy density in electrons and magnetic field is assumed to be less than 1%. Expressions for the peak flux density and time-to-maximum of the radio transients predicted in the Paczyński & Rhoads model at  $\lambda = 20$  cm are given in Frail et al. (1994) for GRB 940301. Since the fluences of the two GRBs were comparable, we expect similar peak flux densities and timescales of 3.6 mJy and 28 days, respectively. A time-variable source of this magnitude and on this timescale would have been readily detectable by our experiment. The above limits are based on the nominal distance, ambient density and efficiencies assumed by Paczyński & Rhoads (1993) and can be relaxed somewhat. For example, the ambient density was assumed to be  $10^{-24}$  g cm $^{-3}$ . Lowering this to a more reasonable  $10^{-27}$  g cm $^{-3}$  shortens the timescale ( $\sim$ 1 day) and reduces the peak flux (1.5 mJy) but again such a fading source would also have been detected.

Mészáros & Rees (1977) have also calculated the emergent spectrum at longer wavelengths at late times. The fireball, formed during the GRB, interacts with the surrounding medium and dissipates its energy in part through shocks. The shocks accelerate particles, which in turn radiate via the inverse Compton and/or synchrotron processes. The emission peaks at a frequency  $\nu_m$  and is self-absorbed below  $\nu_{ab}$ . In time the two frequencies decrease as the fireball decelerates, eventually becoming equal (usually) in the radio regime. The peak flux density and time-to-peak depend not only on the burst fluence and the source distance but also on whether the GRB energy is released impulsively, or in a wind, and on the type of shocks, and the strength of the B-field. Two impulsive models (their models A2 and A3) are the most effective at accelerating particles which radiate in the radio regime. We estimate peak flux densities at 1.4 GHz between 1.7 and 8 mJy on timescales of 40 to 50 days after the burst. The remaining impulsive and wind models do not predict detectable radio emission (i.e.  $< 100$   $\mu$ Jy) at this frequency.

#### 4.2. VLA J1528.7+1945: An Unusual Radio Source

Most of the faint radio sources in the sky are thought to be distant galaxies whose radio emission arises either as a consequence of an active nucleus (with or without extended radio lobes) or from the combination of thermal and synchrotron radio emission which accompanies star

formation. Thus the constancy of the flux on short timescales is understandable. Variations are seen on longer timescales. At meter wavelengths, corresponding to radio frequencies less than a GHz, variations are induced by multipath propagation through the interstellar medium (Mitchell et al. 1994). At frequencies above a GHz, the variations are due to intrinsic changes in the nuclear radio source. As the frequency increases the amplitude of these intrinsic variations (Gregory & Taylor 1986, Machalski & Magdziarz 1993) increase and their timescales decrease. Viewed in this context, VLA J1528.7+1945 is an unusual source because it shows strong variations on short timescales (Figure 2) at a relatively low frequency of 1.4 GHz.

We now evaluate the uniqueness of the source VLA J1528.7+1945. The study of variability in radio sources, especially faint radio sources, on short timescales of days and weeks is still in its infancy. The FIRST survey is a large radio survey of the North Polar Cap, now partially complete (White et al. 1997). The FIRST images have a limiting sensitivity and angular resolution nearly identical to those of our monitoring program which makes it ideal to evaluate the uniqueness (or lack thereof) of our radio source VLA J1528.7+1945. During the course of the FIRST survey, about 75,000 sources were monitored on timescales of days to weeks. A total of fifty sources which showed variations of 25% or larger were identified. Of these only 12 showed variations exceeding a factor of two (Helfand et al. 1996). We refer to this small subset as the extreme variables. From this we conclude that the fraction of extreme variables is  $10^{-4}$ . Thus the mean expectation of the number of extreme variables in our sample of four sources is less than  $10^{-3}$ . While this extreme variable lies in the BeppoSAX-IPN error box it is outside the current best WFC localization for GRB 970111, thus it appears not to be related to the gamma-ray burst. Nevertheless, the source VLA J1528.7+1945 is a highly unusual radio variable and is worthy of further study (Kulkarni et al. 1997).

## 5. Conclusions

The present observations of GRB 970111 are nearly an order of magnitude deeper than a similar comprehensive monitoring effort on GRB 940301. We note that two other GRBs with comparable gamma-ray fluences, GRB 930706 and GRB 920501 were observed with the VLA as early as 9 and 14 days after the burst (Palmer et al. 1995) and no radio sources were reported in these error boxes. Continued long-term monitoring of a dozen arcminute-sized error boxes on timescales of years has also failed to find time-variable radio sources (Frail & Kulkarni 1995) (and Frail et al. 1997b, in preparation). The absence of a flaring/fading radio source at the milliJansky level on these timescales is contrary to the predictions of several models for the late-time emission expected from GRBs at longer wavelengths.

While the detection of a delayed radio counterpart to a GRB would be a breakthrough in the study of these enigmatic objects, a non-detection in itself does not pose a serious challenge to the cosmological model. The underlying particle acceleration mechanisms, their efficiencies, geometry, etc are sufficiently uncertain that the cosmological model cannot be rejected on these

grounds. The VLA observations provide the most sensitive limits which are currently possible at GHz-frequencies and as such they constitute hard constraints that any model has to obey. Since all known gamma-ray sources are radio emitters at some level, we remain hopeful that continued monitoring of bright GRBs will result in the eventual detection of a radio counterpart. Now that BeppoSAX has decreased the positional accuracy to  $\pm 3$  arcmin it has become possible to observe at radio frequencies above 5 GHz, where *all* cosmological models of GRBs predict that the radio emission peaks sooner and at higher flux density levels.

The VLA is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. DAF thanks Jim Condon for his advice on the interpretation of NVSS data. SRK thanks David Helfand for discussion on time variability of the FIRST sources. SRK's research is supported by the National Science Foundation and NASA.

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Fig. 1.— A radio continuum image at 1.4 GHz towards GRB 970111 taken in March 1995, as part of the NRAO VLA Sky Survey (NVSS). The lowest contour is plotted at three times the rms noise of  $0.5 \text{ mJy beam}^{-1}$ , for a synthesized beam size of  $45''$ . The brightest radio source in the image is 135 mJy. The large 10 arcmin radius circle is the earlier BeppoSAX localization. It is intersected by an annulus (two diagonal lines) determined by Hurley et al. (1997b) from the Ulysses and the Compton Gamma Ray Observatory spacecraft. The two smaller circles ( $60''$  radius) mark the positions of the X-ray sources detected by BeppoSAX and ROSAT. The 3 arcmin radius circle is the newest BeppoSAX WFC localization (in 't Zand et al. 1997). The best current error box for GRB 970111 is a trapezoidal region defined by the intersection of the refined IPN annulus and the new WFC error circle. All radio sources detected by our 1997 monitor program are indicated by crosses, with the largest crosses for bright sources ( $S > 10 \text{ mJy}$ ), the smallest crosses for the weakest sources ( $S < 1 \text{ mJy}$ ), and intermediate sizes for  $1 \text{ mJy} \leq S \leq 10 \text{ mJy}$ . All four radio sources in the BeppoSAX-IPN error box, one of which was detected previously by the NVSS, are labeled.

Fig. 2.— Radio light curves for J1528.7+1945 and several comparison sources in the field. The plotted error bars are the  $1\sigma$  uncertainties determined from the Gaussian post-fit residuals (typically 0.1 to 0.3 mJy). J1528.7+1945 is the only variable source in the entire field, with a confidence level which exceeds 99.95%.

TABLE 1. Radio Observations of GRB 970111

Epoch (UT)	$\Delta t$ (days)	Beam (")	$\sigma_{rms}$ (mJy)	$S_{1.4}$ (mJy)
1995 Mar. 04.06		45	0.50	
1997 Jan. 12.58	1.2	1.5	0.17	1.54
1997 Jan. 13.58	2.2	1.6	0.06	1.95
1997 Jan. 15.57	4.2	1.5	0.10	1.97
1997 Jan. 17.62	6.2	1.6	0.11	1.83
1997 Jan. 22.53	11.1	3.0	0.11	1.21
1997 Jan. 26.41	15.0	3.7	0.11	1.30
1997 Jan. 28.57	17.2	3.0	0.15	0.76
1997 Jan. 30.59	19.2	2.8	0.09	1.04
1997 Feb. 05.54	25.1	3.0	0.08	1.01
1997 Feb. 09.41	29.0	2.9	0.06	1.04

Notes to Table 1.

GRB 970111 was detected by BeppoSAX on 1997 Jan. 11.405556 UT.